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PHOTOSYNTHESIS IN SEWAGE TREATMENT*

William J. Oswald, A.M., ASCE and Harold B. Gotaas, M. ASCE**

SYNOPSIS

The stabilization of organic matter in sewage wastes requires oxygen which in secondary treatment plants is normally obtained from the atmosphere. The primary source of atmospheric oxygen is photosynthesis for which the sun supplies the energy and water supplies the oxygen. Sewage contains the necessary nutrients for photosynthetic organisms to produce oxygen while, at the same time, fixing these valuable nutrients as well as solar energy in reclaimable material. Laboratory and pilot plant investigations of sewage treatment in open ponds by photosynthetically produced oxygen have been carried on during the past four years. These studies have provided some basic principles which can be utilized for the engineering design of the process as well as for the prediction of the operational performance of new or existing oxidation ponds. This paper formulates design criteria based on these principles. The chemical, biological, operational, and economic factors which affect the use of engineered photosynthesis as a method for producing oxygen and reclaimable wastes are outlined.

INTRODUCTION

The impounding of domestic sewage and industrial wastes in natural and artificial ponds has been practiced under various circumstances for a long time. In recent years, however, descriptions of pond designs and structures have appeared in engineering literature with increasing frequency, indicating that impounding is emerging as a distinct treatment process. Such facilities have been most commonly called "sewage lagoons" and "industrial waste lagoons." Those more subject to engineering analysis are often termed "oxidation ponds." Lagoons or ponds have been used as holding reservoirs for partially treated effluents from overloaded treatment plants; as leaching reservoirs for percolating liquid wastes into the soil; and to accomplish primary and/or secondary treatment of sewage. Ponds of this kind have certain characteristics in common: They accomplish a degree of treatment by biological oxidation, and they may produce growths of photosynthetic organisms, principally green algae.

Oxidation Pond Types

Studies indicate that oxidation ponds which differ greatly in detention time or physical size, may also differ greatly in the principal mechanism by which oxygen is supplied to newly introduced wastes. For a fixed rate of inflow to ponds of various relative sizes and detention periods the two principal

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mechanisms and corresponding pond types may be shown schematically as in Figure 1.

In oxidation ponds of Type I, having detention periods ranging from three weeks to six months or more, surface aeration is the most important source of oxygen. The larger units of this type which furnish oxygen by dilution, are comparable to natural lakes because their physical size is so great that they may receive wastes with little depletion of their oxygen reserves. The design of such units has been described recently by Van Heuvelen and Svore[1].

The smaller Type I oxidation ponds are commonly designed for detention periods of from three to six weeks. They depend principally upon surface reaeration with atmospheric oxygen, which is accelerated by partial depletion of their oxygen reserve as oxidation of organic matter progresses. The design of this type of pond is described in the literature by Caldwell[2].

Type II ponds utilize detention periods of less than one week. Their small size makes them highly dependent upon the biological process of photosynthesis to yield the oxygen needed for oxidizing the entering wastes. This type of pond has not previously been described in the literature, and thus far has been built only on a pilot scale.

It should be noted as indicated in Figure 1 that no sharp distinctions are made between the pond types because there is overlapping in their oxygenation mechanisms. Photosynthesis, the major source of oxygen in ponds of Type II, may also contribute to the oxygen resources of ponds of Type I whenever conditions are favorable for vigorous algal growth, and also where recirculation is employed. Surface aeration is a source of oxygen for ponds of Type II, especially at night when photosynthetic oxygen production is nonexistent.

The principles of waste treatment by dilution and, to some degree, by surface aeration are described in the engineering literature[3,4]. Little practical data, however, are available on the principles of waste treatment by engineered photosynthesis. It is the purpose of this discussion to present such information, which has been developed in laboratory and pilot plant studies over the past five years.

Photosynthesis

Photosynthesis is the most basic process of biology. Through it green plants are able to make use of solar energy in appropriating carbon dioxide for incorporation into their own organic structure. Photosynthesis represents the ultimate origin of practically all organic matter, and thus is the only important mechanism by which solar energy is stored in a form available for living organisms. It is also the basic mechanism by which oxygen is released from water; and oxygen in turn is the only substance which makes it possible for living organisms to gain sustained access to the energy stored in organic matter. More simply stated, the birth of organic matter by photosynthesis is accompanied by the absorption of energy and the release of oxygen, while the destruction of organic matter involves the tying up of an equivalent amount of oxygen and the release of energy. In general, the value of this equivalence of oxygen and any amount of a specific organic matter may be determined from the elementary composition of the organic matter when newly formed.

Photosynthesis in Sewage Treatment

It is generally recognized that organic matter is most rapidly oxidized biologically by bacteria, and there is much to indicate that it is most rapidly synthesized on a sustained basis by green algae. It is also well known that

the principal products of aerobic bacterial oxidation of organic matter are CO_2, NH_3, and H_2O which, except for the additional requirement of light energy, are identical to the principal requirements for algal photosynthesis. Thus in theory the decomposition of organic matter by bacteria may take place at the same time that new organic matter is synthesized by algae, provided, of course, that light is available as the energy source. Under such circumstances the efficiency of oxygen utilization is greatest because oxygen is used as soon as it is formed. This cycle of photosynthetic oxygen production is shown in Figure 2. Here organic matter entering the system as sewage is oxidized by sewage bacteria utilizing oxygen released by algae. The algae, utilizing solar energy, are simultaneously synthesizing organic matter from hydrogen liberated in their chlorophyll pigments and from the carbon dioxide and ammonia produced by bacteria. Although this entire reaction may take place in a closed system, some carbon dioxide is normally drawn into the cycle from the atmosphere and excess oxygen may be lost.

The cycle shown in Figure 2 is the basic principle on which the Type II oxidation pond of Figure 1 may be operated. In order to develop practical equations for the design of such a unit it is desirable to assume that it will be operated so that all the oxygen required by bacteria will result from the development of new photosynthate. It is desired also to evaluate some of the previously cited basic factors of photosynthesis and to express them in simple mathematical symbols as follows:

1. The relationship between oxygen and organic photosynthate.
2. The relationship between stored energy and organic photosynthate.
3. The relationship between energy stored in organic photosynthate and the solar energy required to produce it.

The weight ratio of oxygen released to organic matter synthesized may be expressed as a factor, p:

$$p = \frac{\text{wt oxygen}}{\text{wt. organic matter}} \text{ or } p = \frac{W_o}{W_{om}} \qquad (1)$$

The available stored energy content (H) of the organic photosynthate is equal to its unit heat of combustion (h) times its weight (W_{om}):

$$H = hW_{om} \text{ or } h = \frac{H}{W_{om}} \qquad (2)$$

The fraction of solar energy (E_s) fixed in the form of organic matter is equal to the total available heat energy (H) of the organic matter divided by a factor (F) which is the efficiency of energy conversion.

$$E_s = \frac{H}{F} \text{ or } F = \frac{H}{E_s} \qquad (3)$$

The ratios from equations 1, 2, and 3 may be combined in such a way as to show the basic relationships between algal cell concentration, depth, detention period, solar energy input, and photosynthetic efficiency in photosynthetic oxygen production. These relationships may then be utilized with certain modifications, to obtain rational values for the physical dimensions of a pond of Type II.

As shown by equation 3 the heat of combustion (H) of algal cell material is proportional to the amount of the total light energy (E_s) which has been fixed, ($H = FE_s$). Since efficiency (F) is dimensionless, both H and E_s should be expressed in the same units. E_s is related to insolation as commonly measured in langleys as follows:

Let: S = insolation in gram-calories per cm^2 per day
A = surface area exposed to light, in cm^2
D = time in days

Then, $E_s = SAD$ (4)

Substituting the value of H from equation 2 and the value of E_s from equation 4 in equation 3: $SADF = hW_{om}$, or $F = \frac{hW_{om}}{SAD}$ (5)

in which W_{om} = wt. of organic matter produced in area A and F is the efficiency of light utilization.

From the considerations shown in the development of equation 4, equation 3 may be written H = SADF. The energy fixed in algal cells (H) may also be found by multiplying the heat of combustion of the algae (h) by the concentration of algae (C_c) expressed in mg per liter rather than as W_{om}. Thus $H = SADF = hC_c$. Since the surface area (A) for one liter of liquid of depth (d) in cm is $\frac{1000}{d}$ sq. cm., then

$$hC_c = \frac{S\ 1000\ DF}{d}, \text{ or } D = \frac{dhC_c}{S\ 1000\ F} \tag{6}$$

Inasmuch as in equation 6 the oxygen demand of a waste is assumed to be met through photosynthetic oxygen production the biochemical oxygen demand (L_t) in any time (t) may be substituted for oxygen produced (W_o); and C_c may be substituted for W_{om}.

$$\text{That is, } p = \frac{Wo}{W_{om}} = \frac{L_t}{C_c}, \text{ or } C_c = \frac{L_t}{p} \tag{7}$$

Combining equations 5 and 7:

$$D = \frac{dhL_t}{1000\ FSp} \tag{8}$$

The efficiency (F) in equations 6 and 8 is modified by many environmental factors. The quantitative effects of each of the several environmental factors are generally unknown. Experimental coefficients representing them can be determined, however, which can then be applied to the factor F. For example temperature profoundly affects both bacterial and algal growth. Hence a temperature coefficient (T_c) is required in equations 6 and 8.

$$D = \frac{dhC_c}{FT_c\ 1000\ S} = \frac{dhL_t}{FpT_c\ 1000\ S} \tag{9}$$

Evaluation of the Design Equation

The actual application of equation 9 to the design of oxidation ponds depends upon a knowledge of the inter-relationships between the several factors in the equation, as well as the influence of environmental factors on the efficiency of algal and bacterial growth.

Depth

The depth (d) of a pond to produce by photosynthesis the oxygen required by a waste can be developed in terms of algal cell concentration (C_c). Experimental data have shown conclusively that a suspension of algal cells absorbs light, within close limits, in accordance with the Beer-Lambert Law:

$$\frac{I}{I_i} = e^{-C_c \alpha d} \tag{10}$$

in which, I is the measured light intensity at depth d, I_i is the incident light intensity, and α is the specific absorption coefficient. Taking the natural log of both sides of equation 10:

$$\log_e I - \log_e I_i = - C_c \alpha d \qquad (11)$$

Since for a practical design it should be assumed that all of the available light is absorbed it follows that at the pond bottom the transmitted light (I) should be approximately zero: Equating I to 1.0 and solving equation 11 for d,

$$d = \frac{\log_e I_i}{C_c \alpha} \qquad (12)$$

Neglecting the possibility of unusual turbidity other than algal cells, equation 12 gives the depth (d) to which light penetrates through a culture. Thus equation 12 defines the effective depth for photosynthetic oxygen production, inasmuch as there is no visible light, and hence no algal growth below depth d.

Since daylight intensities will vary from a few hundred to more than 10,000 foot candles and α and C_c vary from 1×10^{-3} to 2×10^{-3}, and from 1×10^{2} to 3×10^{2}, respectively, it might seem that light intensity would have the greatest effect on the depth of light penetration. Actually light intensity may increase tenfold with but a 33 percent increase in the depth of penetration. On the other hand, reducing cell concentration by a factor of 2 will double the depth of penetration. The value of the coefficient α depends on the algal species and their pigmentation and is not normally subject to close control. In practice, however, it may remain approximately 1.5×10^{-3}. Hence it may be concluded that algal cell concentration is the most important of three factors which determine the depth to which light will penetrate into a pond. The value of d obtained from equation 12 is the depth which normally should be substituted in equations 6, 8, or 9.

Values of the Factor, h.

The heat content of algal cell material is a variable factor. It may be measured by calorimetric methods, or calculated from the chemical content of the algae. In general, it has been shown to be proportional to a factor termed the "R" value, which represents degree of reduction of the organic matter synthesized. If the carbon, hydrogen, and oxygen, of the organic matter is known, R may be determined. Spoehr and Milner[5] have shown that $R = [\frac{(\%\,C \times 2.66 + (\%H \times 7.94) - (\%0)}{398.9}] 100$. It may also be shown that there is a relationship between R and h which closely follows the empirical formula: $h = \frac{R}{7.89} + 0.4$. Thus a hypothetical material having an R value of 60, should have a heat of combustion of about 8 K calories per gram. These relationships have been confirmed in the laboratory by calorimetric methods for algal cell material grown on sewage. Normally for sewage grown algae h is near 6 K calories per gram on an ash free basis.

Values of the Factor, p.

The relationship between the weights of oxygen released and organic matter synthesized varies within relatively narrow limits. As in the case of h, one fundamental method for its evaluation is to measure carbon, hydrogen, oxygen, and nitrogen in the algal cell material. For example: An analysis of a certain culture of algal cells shows C, 59.3 percent; H, 5.24 percent; 0, 26.3 percent; N, 9.1 percent, on an ash-free dry weight basis. By dividing each of these percentages by the atomic weight of the corresponding element

and correcting the resulting numbers proportionately to make the value of the nitrogen coefficient equal to one, the following formula for algal cell material is developed: $C_{7.62}\ H_{8.08}\ O_{2.53}\ N_{1.0}$. Inasmuch as all evidence indicates that ammonia is the source of the nitrogen, carbon dioxide is the principal source of the carbon, and water is the source of the oxygen, it may be assumed that the synthesis of this material followed the equation:

$$1.0\ NH_4^+ + 7.62\ CO_2 + 2.53\ H_2O \longrightarrow C_{7.62}\ H_{8.08}\ O_{2.53}\ N_{1.0} + 7.62\ O_2 + 1.0\ H^+$$

Considering only cell material and oxygen on the right hand side of the equation:

$$(12 \times 7.62) + (1 \times 8.08) + (16 \times 2.53) + (14 \times 1) = 153.56$$

gm cell material.

$$(7.62 \times 32) = 243.84 \text{ gm oxygen.}$$

From which one gram of cell materials is found to be equivalent to 1.587 grams of oxygen. Since algal cell material may contain about 85 percent organic matter, the oxygen yield per gram of ash-included organic matter is 1.587 x 0.85, or about 1.35 grams. Experimental work has shown that under environmental conditions which are practical for photosynthetic oxygen production, the factor, p, normally lies between 1.25 and 1.75. Thus, it may be concluded that synthesis of a unit weight of freshly produced algal cells has been accompanied by the production of a greater weight of oxygen in a form available for bacterial oxidation of organic matter.

Limitations on Efficiency, F:

It is to be expected that every factor affecting living cells will influence the efficiency with which green algae utilize solar energy. No firm value has been established for the maximum efficiency of photosynthesis although it may be more than 50 percent under certain conditions[6]. However for purposes of application to sewage treatment, the question of maximum photosynthetic efficiency is largely academic since a practical barrier to high efficiency occurs long before the maximum reported values are reached.

This practical barrier evolves from the fact that there is a maximum intensity of light which individual algal cells can utilize during a sustained period. All light energy supplied at a higher rate is therefore partially wasted. The critical light intensity above which no additional light is utilized has been termed the "saturation intensity" (I_s). The importance of this factor in pond design is due to its effect in placing a practical upper limit on the efficiency (F) which can be used in equations 6 and 8.

According to Vannevar Bush, as quoted by Burlew[7] the maximum fraction of available light which may be utilized by an individual algae is given by:

$$f = \frac{I_s}{I_i}\left(\log_e \frac{I_i}{I_s} + 1\right)$$

In which I_i is the incident light intensity, I_s is the saturation light intensity and f is the fraction of the available light utilized.

Figure 3 shows graphically how f is influenced by changes in the incident and saturation light intensities. It is evident that as the saturation intensity increases the percentage of incident light which is tuilized also increases. Thus, for example, for an I_i of 8000 f.c. and an I_s of 400 f.c. only 20 percent of the available light energy is utilized, while for I_s of 700 f.c. 30 percent of the energy is used. As I_i increases f decreases regardless of the value of I_s.

Investigations[7] have shown as one result of the foregoing that if algal cells can be brought intermittently into contact with high intensity light through, for example, turbulence created by vertical mixing, the percentage of available light which may be utilized is increased. This increase in the availability of light theoretically increases the depth which can be employed in equations 6, 8, or 9 above that which might be determined by equation 12. Hence the economically effective depth could be greater than the depth determined from equation 12. Further data are required however before any permissible increase in depth can be predicted under conditions of vertical mixing.

The value of I_s is not the same for all cultures of sewage grown algae but rather it is a function of the physiological makeup of the particular cells in the culture. Their mechanisms for light absorption, hydrogen transfer, organic synthesis, and cell multiplication, when functioning at peak efficiency provide the highest saturation intensity. It has been previously demonstrated by the authors[8] that these functions are carried out most effectively by young, rapidly growing cells. Thus cultures in the logarithmic phase of cell growth attain a higher value of I_s and utilize a greater fraction of the available light than do older cultures. To support a population of young cells in the logarithmic phase of growth a substrate rich in nitrogen and other vital elements is necessary. This condition is met only at short detention periods, i.e. low values of D.

Only moderate values of efficiency are practical in sewage treatment because high values of F can occur only in substrates very rich in nutrients, and hence not stabilized. Values of F above 10 percent are believed to be indicative of such a condition. Since the objective of sewage treatment is to produce a substrate depleted in organic matter a relatively low average efficiency during the process is implied.

Temperature data is used to typify the manner in which photosynthetic efficiency is modified by environmental factors. Table I presents typical values for the temperature coefficient (T_c). This table is based upon data for cultures of Chlorella isolated in pilot plant studies and grown in the laboratory at a light intensity of 1200 f.c., illuminated an average of 14.4 hours daily, and at a detention period of 4 days. As previously indicated different values of T_c might be obtained under different experimental conditions and with different species of algae. This fact is illustrated by the observation that the dominant species of algae in an oxidation pond tends to change with the seasons[9]. Sustained low temperatures require consideration. Data obtained in the laboratory indicate that low temperature adaptation is a characteristic of the Chlorella encountered in pilot plant studies[9]. This or comparable strains of algae may be expected to occur in low temperature ponds and will sustain photosynthetic oxygen production down to temperatures approaching freezing. However, as shown in Table I temperature coefficients which modify efficiencies are greatly reduced at the lower temperatures. The rate of bacterial oxidation of sewage is also reduced at low temperatures, and hence it may well become reduced to a point where little oxidation is accomplished, regardless of the oxygen supply. In regard to high temperatures, a strain of Chlorella which has a high temperature tolerance has been reported by Myers[10]. This and other strains will undoubtedly develop under favorable conditions particularly if afforded an adaptation period. However, high temperature as well as low temperature adaptation, may be accomplished at the expense of photosynthetic efficiency.

Values of the Factor S.

The daily amount of solar energy (S) which reaches the earth's surface is a function of astronomical, geographical, and meteorological phenomena. As might be expected it is subject to wide daily and seasonal variation, but on a monthly basis it may be closely predicted at any particular location if certain geographical and meteorological data are available. Table II represents predicted maximum and minimum plausible values of S for the indicated segment of the earth, as calculated by the authors from relationships published by Kimball[11] together with other data collected and published by the U.S. Weather Bureau[12]. Use of Table II to obtain S is illustrated by the following portion of the Table for the month of June at latitude 21°N.

North Latitude		June	
Degree	Range	Vis.	Tot.
21	Max.	285	742
	Min.	150	388

The numbers shown in the rectangles represent the visible and total insolation, (solar radiation), both direct and diffuse, incident on a horizontal surface at sea level, expressed langleys (gram-calories per square centimeter) per day. Values in the right column are total insolation, (ultra violet, visible, and infra red) while those in the left column are the portion of this total radiation which lies in the visible range; that is, the amount of radiation of wave lengths from 4000 A^0 to 7000 A^0 which will penetrate a smooth water surface. The maximum ("max.") values represent in each case the average daily amount of radiant energy which may be received during clear weather. These maximum values are calculated taking into consideration all of the important factors influencing insolation. There is practically no chance that these values will be exceeded over the period of any given month. Minimum ("min.") values represent average daily amounts that may be received during weather with heavy incidence of clouds. These minimums reflect graphic interpolations or extrapolations of minimum observations reported in Weather Bureau records during the ten year period, 1943 to 1952 inclusive. Thus, although these minimum values do not reflect the worst days of record, there is little chance that any of the stations will experience monthly averages appreciably lower.

When corrections are made for elevation and cloudiness in the manner noted at the bottom of Table II, values of visible radiation obtained from the table may be taken as a quantitative measure of the energy available for photosynthesis, that is, as values of S to be used in equations 6, 8, or 9.

Table II may also be used in connection with Figure 4 to estimate a value of I_i to be substituted in equation 12 to determine an approximate value of d for use in equations 6, 8, and 9. Studies by the authors have shown that the mean light intensity for the entire 24 hour period of a day is about 10 times the total insolation expressed in langleys per day, multiplied by the fraction of the time the sun is in the sky. A value obtained by such an estimation is altered by many variable factors and is not subject to precise evaluation. However, this method is relatively accurate for determining the average light

intensity over a period of time, and may be used for the estimation of I_i by the following steps:

1. Obtain the total solar radiation from Table II.
2. Make the necessary corrections for elevation and cloudiness.
3. Multiply the resulting value by 10.
4. Obtain I_i for use in equation 12 by multiplying the result of Step 3 by the fraction of time the sun is in the sky for the appropriate latitude and month as obtained from Figure 4.

For example following the above steps a station at latitude 37° elevation 2000 feet with clear weather 50 percent of the time may have a mean light intensity in December of approximately 870 f.c. on a horizontal surface.

Influence of Chemical Factors

Nitrogen

The authors have[13] collected considerable evidence which indicates that the species of algae that are effective in photosynthetic oxygen production utilize ammonia as the principal source of nitrogen with which to build their proteinaceous cell material. At moderately long detention periods of 3 or 4 days when temperature and light are optimum, practically all of the available ammonia nitrogen appears in the form of algal cell material. In this way nitrogen is conserved and at the same time the ultimate oxygen demand of a waste is greatly diminished because little ammonia remains to be oxidized to nitrate.

Under some conditions, supernatant analyses show the presence of reduced nitrogenous compounds. Although a small carry-over of sewage, unoxidized during the short detention periods normally effective in the process can occur, the amount of this material increases with increasing detention periods which indicates that a small amount of inseparable organic matter is produced in the process. A portion of the nitrogenous material is fixed in living bacterial cells which are dispersed as colloids and are discharged in the supernatant. Whatever the nature of this supernatant nitrogen, under proper operating conditions it normally amounts to less than one-third the total nitrogen in the waste, while the remainder appears in the algal cells.

The nitrogen content of a waste places a practical upper limit on the concentration of cell material which can be developed from it. A useful "rule of thumb" relationship between sewage nitrogen and growing algae is that $C_c = 10 \times N$, where C_c -maximum algal cell concentration, and N-nitrogen, are expressed in the same units. The constant 10 stems from the assumption that 80 percent of the nitrogen in the waste is recovered and that algal cells are 8 percent nitrogen. For example it has been observed that a waste containing 30 ppm of total nitrogen will support $\frac{.8 \times 30}{.08} = 300$ ppm of algal cells before nitrogen becomes a limiting factor to cell growth.

Phosphorus

Phosphorus rarely becomes a limiting factor to algal growth in sewage. The best information now available indicates that phosphorus does not normally exceed 1.5 percent of the dry weight of algae. In this case a typical sewage containing upwards of 6 ppm of phosphorus would sustain an algal concentration of over 400 ppm if all the phosphorous were available. Increased use of detergents in the home and in industries make it unlikely that either phosphorus or nitrogen (both components of detergents) will be limiting factors in the nutritional makeup of domestic sewage.

Magnesium and Potassium

Both magnesium and potassium are essential to algal growth. Magnesium is essential because it is an integral part of the chlorophyll molecule and potassium because salts of this metal are prime constitutents of algal cell sap. Normally domestic sewage contains more than 5 ppm of both of these elements. Since algal cells may contain 0.5 percent potassium and 1 percent magnesium it can be concluded that if these elements are fully available domestic sewage contains them in sufficient amounts to support algal concentrations in excess of 500 ppm.

Carbon

Carbon is usually the limiting element when algae are cultured on sewage. However the use of artifically introduced carbon is neither essential nor desirable when algae are cultured in sewage for purposes of photosynthetic production of oxygen. Although the amount of carbon contained in sewage may be inadequate to produce sufficiently large growths to meet the oxygen demand of the waste, the culture may also obtain carbon dioxide from the air. Active photosynthesis causes the pH to increase up to 10 or more accelerating the absorption of atmospheric CO_2 by the culture. Under such conditions this CO_2 appears in the solution as bicarbonate ion and becomes available to the algae at once. From this it is seen that algae may compensate for a shortage of CO_2 by increasing the CO_2 absorbing properties of the solution in which they grow.

BOD

The BOD test is unique in its significance as a measure of the response of microbial growth to the nutritional character of wastes. Figure 5 shows effect of the BOD of a sewage on the algal growth it will support. It is noteworthy that in continuous cultures such as those reported in Figure 5 the dry weight of algal cell material appears to be logarithmic function of BOD up to approximately 400 ppm. Evidence indicates that for BOD values greater than 300 ppm light rather than nutrition is normally limiting to outdoor algal growth. The effect of increasing light intensity above that shown for the tests in Figure 5, would be to increase culture density slightly. However the shape of the curve would remain similar.

Actual laboratory tests are needed to determine whether a given domestic sewage will support the amount of algal growth necessary to produce its oxygen requirements by photosynthesis.

Practical Design Considerations

Detention Period

Inasmuch as the detention period (D), as shown in equation 9, is a function of light and temperature, theoretically it should be capable of much greater variation than is possible in practical pond design. For example to apply equation 9 to a sewage having a BOD of 150 ppm under December conditions at Latitude 37° it may be assumed that $p = 1.5$, $h = 6.0$, $d = 30$ cm, $F = 0.1$ and $T_c = 0.87$. From Table II, S (min.) may be taken as 34 langleys per day. Using these values it is calculated that a detention period near 6 days might be required for complete sewage treatment. In the summertime the efficiency of a pond designed for such a detention period would become very low. Without proper variations in operating procedures, the result could be over-production of algae, a part of which might die and decompose thus producing a pond effluent having a high supernatant BOD. On the other hand, if a pond were

designed for the same location on the basis of June light and temperature conditions using S (avg) = 234, T_c = 1.0, and other factors remaining the same, from equation 9 a detention period of only 0.77 days is obtained. Pilot plant units have been successfully operated at detention periods as low as 0.75 days for sustained periods, with otherwise optimum environmental conditions, and Chlorella as well as other algae easily maintains a rate of growth sufficient to prevent being diluted out of the pond under these conditions. However it has been found from pilot plant experience that cultures cannot withstand either low temperatures or a long succession of cloudy days at this low detention period without some nuisances occurring. Hence if a pond were to be designed for the June conditions previously stated it would be better to increase the detention period and the pond depth. For the stated June conditions of light and temperature the depth (d) by equation 12 is increased to 48 cm, in which case the detention period by equation 9 would become 1.25 days, a value more in keeping with the growth capabilities of organisms under varying outdoor conditions. In order to provide a detention period suitable for effective photosynthetic oxygen production in both winter and summer and with "buffer capacity" against changes in light and temperature and against shock loading, certain compromises are necessary. In some cases it might be feasible to design with the expectation that only about 50 percent of the BOD would be removed by the process in winter when, because of low temperatures and higher stream flow, complete treatment should not be necessary. It would be unnecessary to produce oxygen photosynthetically when the temperature was too low for a high rate of bacterial oxidation.

In general it may be concluded that for most conditions detention periods should not be less than one day for summer conditions nor more than six days for winter conditions. A pond having a detention period of about three days and a depth of 12 inches should, for example, satisfactorily produce adequate oxygen by photosynthesis more than 80 percent of the time in latitudes up to 40°N, providing that continuous freezing conditions do not prevail. Under summer conditions it may be calculated that Type II ponds should operate successfully as far north as the artic circle or beyond.

Depth

As previously shown by equation 12 the depth of a pond for effective photosynthetic oxygen production depends upon light intensity, as well as upon light absorption and algal cell concentration. From equation 9 it may be observed that calculated depth varies greatly with both the cell concentration (C_c) and the sewage strength (L_t). Strong wastes requiring dense algal growths must therefore be treated in relatively shallow ponds while weak domestic sewage may be processed at larger depths. The appropriate depth required for treating a particular sewage may be calculated as illustrated in the following example. Assuming that the sewage has a BOD of 125 ppm, that p is 1.25, I_i has a mean value of 1500 f.c. and α is 1.2×10^{-3}; then from equation 12,

$$d = \frac{\log_e I_i}{\alpha C_c} = \frac{\log_e 1500}{1.2 \times 10^{-3} C_c} = \frac{6000}{C_c} \text{ (Approx.)}$$

From equation 7,

$$C_c = \frac{L_t}{p} = \frac{125}{1.25} = 100.$$

Hence

$$d = \frac{6000}{100} = 60 \text{ cm, or about 2 feet}$$

Organic matter at depths below this value would presumably be in darkness and not subject to photosynthetic oxygenation. If a waste with a BOD of 1250 ppm had been utilized in the calculations a depth of light penetration less than 3 inches would have been obtained. Factors such as economic utilization of land, pond construction costs, mixing methods, etc. place a practical lower limit on the depth of the pond and a practical upper limit on the concentration of wastes. For instance, wastes of BOD greater than 300 ppm result in calculated depths so shallow that pond areas become very large. In such cases vertical mixing or primary dilution should be considered as alternatives to shallow depths.

Deposition of Sludge

Rapid oxidation of organic matter in a pond accelerates the deposition of sludge, which may become so dense near the pond inlet as to include more than 50 percent of the influent organic matter. Such sludging has been observed in oxidation ponds of all types, especially in those having only a few inlets. Small, and long narrow ponds are more subject to this difficulty than are large or broad ones indicating that wind mixing is beneficial in the open structures. These anaerobic sludge deposits tend to exclude light, retain nutrients needed by the algae in the liquid, and hence decrease permissible pond depth. Suggestions for combating sludging by proper design considerations include reduction of depth, increasing dilution factor, distributing the load by multiple inlets, orientation of pond to obtain wind mixing and furnishing turbulence by vertical mixing.

If a Type II pond is to be maintained aerobic by photosynthetic oxygen production, despite sludge deposition, it must be kept shallow so that light penetrates a relatively large portion of the volume, or some form of vertical mixing must be employed. Present evidence indicates that vertical mixing is particularly desirable if algal cell recovery is to be practiced. In this case maximum algal growth is encouraged because the products of bacterial oxidation are made uniformly available to the algae in the light. It is probable that some artificial vertical mixing must be considered an essential feature for Type II oxidation ponds. An evaluation of the optimum amount of vertical mixing is now under investigation.

Recirculation

Pilot plant studies have indicated that recirculation is important to photosynthetic oxygen production because it permits seeding of influent sewage with algal cells and brings abundant oxygen into it. In other words recirculation produces good overlapping of bacterial oxidation and of photosynthetic reduction, thereby preventing loss of CO_2 and ammonia from the bacterial phase and providing an efficient outlet for the oxygen liberated by algal growth[8]. This overlapping produces more abundant growths of bacteria and would produce more abundant growths of algae were it not for the problem of sludge deposition. Whereas algae tend to remain dispersed in the solution, bacteria tend to form a floc which together with coagulated sewage colloids containing a large part of the carbon and nitrogen, settles quite rapidly to the bottom of the pond. While some recirculation accelerates sludge deposition with the accompanying possibility of anaerobic conditions in the sludge layer as well as the withholding of nutrients from the algae in the liquid. Since the principal benefits of recirculation are seeding and aeration of the influent, it is possible that these benefits may be duplicated by increasing the uniformity of load distribution together with a low rate of recirculation to accomplish seeding.

Retention of Sludge

If continuous vertical mixing is employed some aerobic sludge may be carried into the pond effluent. This material may be readily removed from the algal suspension by sedimentation and returned to the pond. If intermittent vertical mixing is used, carryover of sludge may be prevented by interrupting the discharge of effluent during and shortly after the mixing period. In either case retention of sludge is advantageous since it allows more complete oxidation of the organic matter, resulting in increased algal growth and improved removal of suspended solids other than algae.

The Need for Paving

Several factors suggest the possibility that there may be important advantages gained by lining oxidation ponds of Type II. Any form of vertical mixing considered essential to raise precipitated sludge and increase light utilization might cause undue turbidity in unpaved ponds. The result would be reduction if not termination of photosynthesis. Furthermore, unpaved ponds designed to make full use of winter sunlight might have excess light at the bottom in the summer, a factor which would doubtlessly encourage growth of water weeds such as tule.

Asphaltic or rubber membranes sprayed over shaped and compacted earth appear to be an economic type of pond lining. Sealed asphaltic concrete or thin reinforced concrete would have the advantage of durability and low maintenance. The possibility of application of commercially manufactured preformed channels of plastic or aluminum should not be overlooked. The design and fabrication of economical pond linings does not appear to be a difficult technical problem since the indicated pond size of near one half acre per thousand population is not prohibitively large. The decision on linings depends primarily upon the value of photosynthate in the sewage treatment process.

Disposal of Algae

In the process of producing controlled quantities of oxygen for bacterial stabilization of waste the concentration of algae produced in moderately strong domestic sewage (200 ppm BOD) may attain levels in excess of 300 ppm dry weight. Two questions immediately arise: What is the effect upon a receiving body of water of algae discharged with the pond effluent? And, can these algae be economically separated from the effluent?

In answer to the first question it should be noted that there is a limit on the concentration of algae which can survive in any body of water for a sustained period of time. Algal cells are living organic matter which may grow, vegetate, or die. If the cells grow they will produce oxygen. If they vegetate they will have a small but finite continuous oxygen demand. (For sewage grown algae by Warburg measurement this usually is about 1/10 of the ash free dry weight of cells per day at 25°C.) If they die they will decompose like any other organic matter. Which of these three possible avenues the cells will first take depends upon the environment in the receiving water. As discussed by the authors in an earlier paper[14], if the receiving water contains nutrients (indicating pollution) and light the cells will grow and divide thus producing oxygen. If there is light but few nutrients the cells will vegetate for long periods of time producing little objectionable pollution in a stream. Cultures of algae having concentrations of two or three hundred parts per million have been held for three months without putrefaction as long as light and access to atmospheric CO_2 are afforded. Ultimately however, the cells will settle to the bottom. In the dark algae remain alive a length of time

which is principally a function of temperature. Algal cells will keep in the dark for 2 weeks at temperatures near freezing but will die and decompose in a few days at temperatures above 25°C. It may be concluded that living algal cells will do little pollutional damage to receiving waters unless their concentration is so large that their endogenous respiration depletes the oxygen reserve of the water. However, should algal cells for some reason be killed in the receiving waters they will exert an oxygen demand approximately equivalent to their dry weight.

Economical separation of algal cells is a highly important aspect of the general use of photosynthesis in sewage treatment. At least two systematic investigations have been conducted recently on algal separation and three processes have been demonstrated to be technically effective. Two of these processes, centrifugal separation, and alum coagulation, have been partially investigated by the authors and other methods are scheduled for investigation. Steele and Gloyna[15] performed a series of investigations on screening and filtering devices for separating algae. These showed rather conclusively that separation of algae is a difficult and costly procedure which may require extensive research and development before the most economical procedures are established.

Because of the relatively low concentration at which algae grow, the cost of separation is almost completely proportional to the volume of liquid processed and relatively independent of the concentration of algae in the liquid. Therefore, some level of algal concentration may be attained which will pay for the cost of harvesting while some higher concentration might support the entire photosynthetic process.

Pond Performance

Algal Yields

Pilot plant observations summarized in Figure 6 show that the rate of algal yield may vary from one ton per acre per month in the winter to five tons per acre per month in the summer. The total annual rate of yield was 30 tons per acre. In order to visualize such yields it is useful to compare yields of algae to field crop yields. During 1953 the average field crop yield in California was less than 1.5 tons dry weight per acre per year. Thus the rate of yield attained in the pilot plant was 20 times the agricultural average. Actual annual yield of algae may be expected to vary strongly with light and temperature and hence with geographical location.

BOD Removal

The operation of an oxidation pond to produce maximum algal yields can at the same time accomplish a good degree of sewage treatment in terms of BOD removal. Data from pilot plant experiments shown in Table III, demonstrates that effluents of the quality desired in sewage treatment may be produced. It is believed that samples 2, 3, and 4 would have exerted much less BOD in a stream than indicated from the data because the residual algae contained would have continued to produce some oxygen following discharge.

Coliform Removals

In laboratory and pilot plant tests no reduction in coliform organisms other than normal die-away has been noted, except in certain light-saturated cultures. In these cultures it is probable that the germicidal effect of natural sunlight was responsible. In other words, no specific anti-coliform activity can be credited to the algae produced in the cultures tested. These findings

were supported by inoculating a solid medium made up with 25 percent porcelain filtered pond supernatant with human intestinal coliform. Since the coliform organisms were found to grow abundantly on this medium the indication is that no specific anti-coliform substance was present in the samples tested. It should be noted that if an adequate separation procedure is employed to remove algae, extensive removal of coliform as well as other bacteria should be attained.

Odors

During the 2 years of operation of the pilot plants under proper conditions no odors have been observed with the exception of a faint grassy odor which is a characteristic of the process. These observations include the all-night periods wherein the pond was undergoing high loadings. When the ponds were overloaded in a deliberate attempt to break down the photosynthetic process foul odors were noticeable. These resulted principally from anaerobic bottom sludges brought to the surface during stirring. Under proper operating conditions photosynthetic oxygenation is a process without objectionable odors.

Contaminants

Any biological or chemical agent which interferes with the process of green algal growth may be considered a "contaminant." Chemical contaminants are those materials which may occur in sewage and are specifically toxic to algae. Although this factor has not been studied directly, indirect evidence indicates that such chemicals normally do not attain concentrations high enough in sewage to destroy the algal population.

Blue green algae, some of which are toxic to animals, could conceivably ruin the algal cell material as a useful food product. There is little evidence of any tendency for blue green algae to grow in fresh domestic sewage. In two years of open air pilot plant operation blue green algae have appeared only in negligible concentration.

The principal contaminants found in pilot plant studies were green algae of the genus Chlamydomonas. These organisms grow swiftly, covering the pond surface with a foamy scum in a matter of one or two days. This scum shuts out light from underlying strata and hence interrupts oxygen production. Fortunately Chlamydomonas blooms are of short duration and the organisms are easily skimmed from the pond surface by means of wind or jet skimming.

Economic Factors

Reclamation of Nutrients

Green algae, growing in wastes, are capable of accumulating needed elements from solutions that contain these elements only in minute concentrations. Thus green algae have great potential as agents of reclamation. For example, in growth unit experiments algae growing in sewage were supplied a small excess of carbon dioxide. As a result all but a trace of ammonia nitrogen was incorporated in algal cell material. If a culture is supplied air containing 0.03 percent CO_2, 60 to 80 percent of the sewage nitrogen is fixed in algal cell material within a few days. Similar reclamation of other critical elements occurs. The indication therefore, is that photosynthesis for waste reclamation may have intrinsic values to the national economy over and above its usefulness as a sewage treatment process. This may be further understood when it is considered that sewage is not truly a waste. Derived from the most nutritive photosynthate harvested from the land, sewage

contains the low energy forms of every element critical to life. Nitrogen might be taken as a typical example. Nitrogen is essential in the human body and yet if a daily nitrogen balance were made on a normal human subject, it would be difficult to demonstrate any significant utilization of nitrogen, as the amount excreted would be found to be almost identical to the amount consumed. Only the form and energy level of the nitrogenous compounds would be changed. Living animals are thus in dynamic equilibrium with their environment and the amounts of critical elements permanently affixed in their bodies are negligible when compared with the total amounts which are consumed and excreted during their lifetime. Thus excreted organic matter has undergone little more than a reduction in its chemical energy content and it would be surprising if it were not an ideal medium for algal growth.

Mention should be made also of some of the possibilities of this process for water reclamation. For example, the amount of water required to produce a pound of protein by this process can be calculated to be less than 1/100th that required to produce an equivalent amount of protein by conventional agricultural methods. This is mainly due to the relatively high photosynthetic efficiency of the process. When coagulation is used for algal removal, effluents are of high quality and there does not appear to be any technical reason why they could not directly supplement a water supply if first processed by sand filtration and chlorination.

Algae as Food and Raw Material

Burlew et al[7] have reported the value of algae as a food and as a source of industrial raw materials. Sewage-grown algae has been fed satisfactorily to a number of animals with no evidence of toxic effects. One group of chicks received dried sewage grown algae as their sole source of protein. Gain in live weight of these chicks average 4.2 percent per day[16]. This may be compared with a maximum gain for chicks of approximately 8 percent per day obtained with a protein mixture considered ideal. From this, as compared with vegetable protein, the value of sewage grown algae as a chicken feed supplement should be approximately $100.00 per ton.

In tropical areas of the world which receive much solar energy but often lack fixed nitrogen and other essential elements for food production, it is possible that the photosynthetic process could be applied to recycle these elements, thereby greatly increasing the food supply.

The fuel characteristics of dry algae are similar to those of medium grade bituminous coal although their heat content is somewhat less, ranging up to 10 thousand BTU per pound. For some time to come, however, the food value of dry algae will probably be its greatest economic value.

The high protein content—more than 50 percent—is not the only important quality of algae. Algae may become an important source of vitamins, of starting products for organic synthesis, or as organic collectors of elements such as germanium which algae concentrate. Exploration of these possibilities has been seriously restricted by a lack of algae with which to experiment. It is possible that one or more of these uses could at once make sewage treatment by photosynthesis an economically feasible process.

Plant Costs

No attempt will be made to present detailed estimates of the cost to build and operate a plant to treat sewage by photosynthetic oxygenation. The cost of each plant where the process might be used must be evaluated specifically in accordance with the design principles set forth. It does appear that the total cost for a plant to grow algae would be less than that for conventional

secondary treatment when the cost of land is not excessively high. The development of economical methods of harvesting the one to one-and-one-half tons of algae which can be grown per million gallons of sewage might bring the actual cost much below that of conventional treatment because of the value of the harvested algae.

SUMMARY AND CONCLUSIONS

Oxidation ponds are classified in accordance with the principal source of oxygen. Type II ponds in which oxygen is produced essentially by photosynthesis can be designed much smaller than ponds of Type I in which the necessary oxygen is supplied primarily by surface aeration.

Basic rational formulations for pond detention periods and pond depths are derived utilizing the law of conservation of energy together with solar energy data and data on the light transmitting characteristics of algal cultures. The application of these formulations to Type II pond design are illustrated and discussed. When design cirteria are correctly applied, photosynthetic oxygenation will result in sewage treatment equivalent to complete treatment obtained by other methods.

Successful technical design of the photosynthetic oxygenation process requires consideration of the influences of such variables of light, temperature and sewage quality on symbiotic bacterial and algal growth. Although interrelationship between these variables is complex, when applied to algal growth their effects can be conveniently incorporated into design equations as coefficients. No firm value can be assigned the overall photosynthetic efficiency because of the modifying effects of environmental factors which are largely unknown. For the present a value approaching 0.1 can be attained in experimental work while values exceeding 0.20 do not appear likely because of the limited ability of algae to utilize light of high intensity.

Before photosynthetic oxygen production in Type II ponds can attain its maximum potential as a practical form of sewage treatment, economical methods for algal separation must be further evaluated, developed, and demonstrated.

The technical feasibility of photosynthetic oxygenation in sewage treatment may be considered an accomplished fact. The reclamation of food from sewage as algae, appears very promising but practical attainment will be deterred pending further investigation of separation procedures. More studies of photosynthetic efficiency, separation of and other factors—particularly the value of the algal cell materials produced in the process—are necessary.

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REFERENCES

1. Van Heuvelen, W., Svore, Jerome H., Sewage and Industrial Wastes 26, 6, 771 (1954).
2. Caldwell, D. H., Sewage Works Journal, 18, 3, 433 (1946).
3. Phelps, Earle B., "Stream Sanitation." John Wiley and Sons (1944).
4. Imhoff,Karl, Fair, G. M., "Sewage Treatment." John Wiley and Sons (1940).
5. Spoehr, H. A., Milner, H. W., Plant Physiology, 24, 1, 120 (1949).
6. Burk, Dean and Warburg, Otto, Naturwissenschaften, 37, 24, 560 (1950).
7. Burlew, John S., "Carnegie Institution of Washington, Publication 600," The Kirby Lithographic Co. (1953).
8. Oswald W. J., Gotaas, H. B., Ludwig, H. F., and Lynch, V., Sewage and Industrial Wastes, 25, 1, 26 (1953).
9. Gotaas, H. B., Oswald, W. J., Ludwig, H. F., Scientific Monthly, 79, 6, 368 (1954).
10. Myers, J., "Carnegie Institution of Washington, Publication 600." The Kirby Lithographic Co. (1953).
11. Kimball, H. H., Monthly Weather Review, 63, 1, 1, (1953).
12. U. S. Dept. of Agriculture, Monthly Weather Review, 71 to 77 inc. and U. S. Dept. of Commerce, Climatological Data National Summary, 1 to 3 inc. U. S. Govt. Printing Office (1943-1953).
13. Oswald, W. J., Gotaas, H. B., Ludwig, H. F., and Lynch, V., Sewage and Industrial Wastes, 25, 1, (Jan., 1953).
14. Ludwig, H. F., Oswald, W. J., Gotaas, H. B., and Lynch, V., Sewage and Industrial Wastes, 23, 1337 (Nov., 1951).
15. Steel, E. W., Gloyna, E. F., "Oxidation Ponds-Radioactivity Uptake and Algae Concentration," Sanitary Engineering Laboratory, Dept. of Civil Engineering, University of Texas (1954).
16. Grau, C. R., Personal Communication (1954) and Journal of Nutrition 41, 1, (1950).

TABLE I
Temperature Coefficients
For Pilot Plant Chlorella

Mean Temperature Degrees		Photosynthetic Temperature Coefficient (T_c)
C	F	
0	32	—
5	41	0.26
10	50	0.49
15	59	0.87
20	68	1.00
25	77	0.91
30	86	0.82
35	95	0.69
40	104	—

TABLE 11

SOLAR RADIATION[a]

Probable Average Values of Insolation—Direct and Diffuse—on a Horizontal Surface at Sea Level, in Langleys[b] per Day

NORTH LATITUDE		MONTH																					
		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Degree	Range	vis	tot[c]	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot	vis	tot
	max	255	665	266	700	271	708	264	690	249	645	236	626	238	630	252	666	269	690	265	694	256	663	253	667
0	min	210	560	219	583	206	536	188	482	182	480	183	274	137	368	167	432	207	533	203	530	202	543	195	527
	max	256	670	263	693	271	706	267	697	253	656	241	642	244	646	255	673	269	693	262	688	251	666	248	646
2	min	206	560	213	560	204	534	188	464	184	484	188	288	141	375	169	442	208	531	200	523	196	520	189	505
	max	244	656	259	688	270	704	268	701	258	665	247	656	250	657	258	678	269	695	260	680	246	650	244	628
4	min	200	540	206	543	202	532	187	460	187	492	113	300	146	385	171	448	204	529	196	513	194	510	183	480
	max	238	630	254	675	268	702	270	705	262	675	252	668	255	669	261	683	269	697	256	670	240	624	238	610
6	min	193	520	199	530	200	530	186	467	189	500	118	310	150	395	172	452	202	524	191	500	188	494	178	460
	max	230	610	249	665	267	700	270	709	268	685	258	678	260	680	263	688	267	695	252	660	234	616	231	590
8	min	187	495	192	510	196	523	185	467	191	506	124	320	154	405	174	456	200	518	185	486	182	478	169	440
	max	223	595	244	655	264	694	271	711	270	694	262	688	265	690	266	693	266	693	248	650	228	600	225	570
10	min	179	475	184	490	192	513	183	464	192	512	128	330	158	414	176	460	196	510	181	474	176	462	162	420
	max	216	572	239	645	262	690	271	710	273	702	267	700	269	710	267	697	264	691	244	640	221	585	217	550
12	min	172	455	176	470	189	500	181	462	193	510	133	343	161	421	178	464	193	502	176	462	169	446	154	400
	max	209	555	233	630	258	680	271	709	276	710	272	710	273	758	269	700	262	686	240	627	214	567	209	536
14	min	163	430	167	450	184	487	179	460	194	524	137	354	164	429	177	467	189	496	170	449	162	430	146	380
	max	200	530	226	610	255	670	272	707	279	718	276	720	277	715	270	703	259	684	234	615	208	554	200	520
16	min	154	400	159	430	180	473	177	456	194	528	141	363	167	435	177	469	185	489	164	434	154	410	138	360
	max	192	515	220	590	250	664	272	705	282	723	280	726	280	723	272	705	256	680	229	605	198	538	192	500
18	min	144	380	150	410	174	458	174	452	194	530	145	375	170	442	177	471	180	479	157	418	146	390	129	340
	max	183	500	213	575	246	652	271	703	284	730	284	736	282	729	272	706	252	674	224	596	190	520	182	480
20	min	134	360	140	390	168	440	170	447	194	532	148	383	172	450	177	472	176	467	150	400	138	370	120	320
	max	174	480	206	560	241	644	270	701	286	734	286	747	285	736	273	707	248	668	218	582	183	500	172	460
22	min	123	335	132	370	162	426	167	440	193	530	152	392	173	454	176	472	170	455	143	380	128	350	110	300
	max	166	460	200	545	236	628	268	697	288	738	290	753	287	742	273	708	244	659	212	568	178	480	161	440
24	min	111	310	123	340	156	410	164	433	191	525	155	403	176	459	174	471	165	443	136	360	119	320	101	280
	max	156	440	192	530	230	615	266	690	288	741	292	760	288	749	273	708	240	652	205	552	166	460	149	420
26	min	99	280	114	310	149	390	160	425	189	518	158	409	177	463	172	469	160	429	128	332	109	300	90	260
	max	148	420	184	510	224	603	264	683	289	743	294	764	288	755	272	704	236	635	199	537	157	440	138	400
28	min	87	250	108	290	142	373	156	415	187	506	161	418	178	467	169	468	154	415	120	310	99	278	80	236
	max	136	400	176	490	218	587	261	675	290	744	296	768	289	759	271	702	231	625	192	524	148	420	126	380
30	min	76	220	96	260	134	362	151	405	184	490	163	425	178	469	166	462	147	399	113	290	90	256	70	210
	max	126	380	169	470	212	570	256	663	290	744	296	772	289	761	269	700	226	615	185	510	138	400	114	360
32	min	63	186	87	240	126	340	146	395	181	475	166	431	178	472	163	468	140	385	104	276	80	224	60	184
	max	114	360	160	450	204	553	254	657	290	743	297	775	289	763	267	696	221	602	178	490	128	380	101	338
34	min	53	155	78	215	118	320	141	385	176	462	168	439	178	472	159	448	134	368	96	250	70	202	47	158
	max	103	335	150	430	196	530	250	650	288	741	298	776	289	765	264	690	215	590	170	470	118	360	88	314
36	min	44	133	70	200	111	300	136	375	172	444	170	443	177	472	154	438	127	350	88	230	60	180	38	134
	max	90	310	140	415	189	520	246	640	287	738	298	778	288	766	262	684	210	576	162	450	108	336	77	290
38	min	36	120	62	180	103	280	131	365	168	428	171	448	175	464	152	429	120	330	80	216	50	158	30	111
	max	80	280	130	390	181	500	241	630	286	732	298	779	288	765	258	680	203	562	152	430	95	313	66	270
40	min	30	105	53	160	95	270	125	356	162	415	173	450	172	455	147	416	112	310	72	202	42	134	24	94
	max	68	255	119	370	172	485	236	616	283	728	298	777	287	761	254	670	196	547	144	410	84	289	56	244
42	min	24	90	45	140	88	250	120	344	157	405	174	451	167	442	143	403	105	290	65	187	34	112	19	78
	max	55	220	106	340	160	470	230	607	280	722	296	777	285	755	250	660	189	530	132	390	72	263	47	218
44	min	20	80	37	130	80	230	114	325	153	395	175	453	164	438	138	389	98	270	58	173	28	96	15	62
	max	45	200	94	315	156	456	224	598	276	716	294	776	284	749	245	650	181	512	122	370	61	238	39	194
46	min	16	74	30	110	72	210	108	315	150	385	175	458	161	420	134	374	90	250	52	156	23	86	11	48
	max	35	180	82	290	149	430	218	582	274	710	297	778	282	740	241	640	174	496	111	350	50	210	32	170
48	min	12	64	25	98	64	190	102	287	146	378	176	460	158	418	129	358	81	230	45	144	18	70	9	37
	max	28	164	70	265	141	410	210	568	271	703	297	778	280	733	236	625	166	480	100	329	40	183	26	144
50	min	10	54	19	80	56	172	97	260	144	371	178	458	155	403	125	342	73	210	40	130	15	60	7	30
	max	22	140	60	240	134	390	202	555	267	695	296	776	278	725	232	615	158	460	87	287	32	160	21	121
52	min	8	45	14	62	51	158	92	246	141	365	176	460	163	398	120	329	65	190	34	120	12	53	4	27
	max	16	128	50	215	126	370	194	542	261	687	296	776	276	720	224	602	150	440	76	265	25	140	16	99
54	min	5	40	11	45	46	145	86	229	139	360	176	460	150	384	116	312	58	170	29	106	9	43	3	23
	max	12	102	43	200	120	350	188	528	256	680	295	775	273	714	218	587	141	429	66	241	20	120	12	78
56	min	4	35	8	35	41	132	80	203	136	352	175	460	148	390	110	297	51	150	24	95	7	36	2	18
	max	9	80	37	170	113	330	182	516	254	670	294	774	270	712	212	575	134	402						
58	min	3	28	6	28	37	116	82	277	134	346	175	460	146	385	106	285	44	132						
	max	7	64	32	150	107	316	176	508	249	660	294	773	268	708	205	556	126	386						
60	min	2	20	4	20	33	100	79	270	132	340	174	460	144	380	100	270	38	116						

Algae Research Project
Sanitary Engineering Research Laboratory
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University of California, Berkeley
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[a] Calculated from data published by the United States Weather Bureau.

[b] Gram calories per square centimeter.

[c] "Visible" = radiation of wave lengths of 4000A° to 7000A° penetrating a smooth water surface.

[d] "Total" = radiation of all wave lengths in the solar spectrum.

[e] Value which will not normally be exceeded.

[f] Value based on, or extrapolated from, lowest values observed for indicated month and latitude during 10 years of record.

Approximate corrections for elevation up to 10,000 ft.:

1. Total radiation: tot (1 + 0.0185 El.)
2. Visible radiation: vis (1 + 0.00925 El.)

Where El. is in thousands of feet.

Correction for cloudiness (approximate):

Min + [(max − min) cl.]

Where cl. is fraction of time weather is clear.

TABLE III

Typical Values for BOD as A Function of Separation Procedure Following Photosynthetic Oxygenation

No.	Sample	Separating Procedure	BOD	% Removal
1	Influent	None	210 ppm	0
2	Pond	No Separation	195 ppm	7
3	Tailing	Settling 1 hour	105 ppm	50
4	Tailing	Laboratory Centrifuging 10 min. at 500 times gravity	25 ppm	88
5	Supernatant	Coagulation (followed by 30 minutes settling)	9 ppm	96

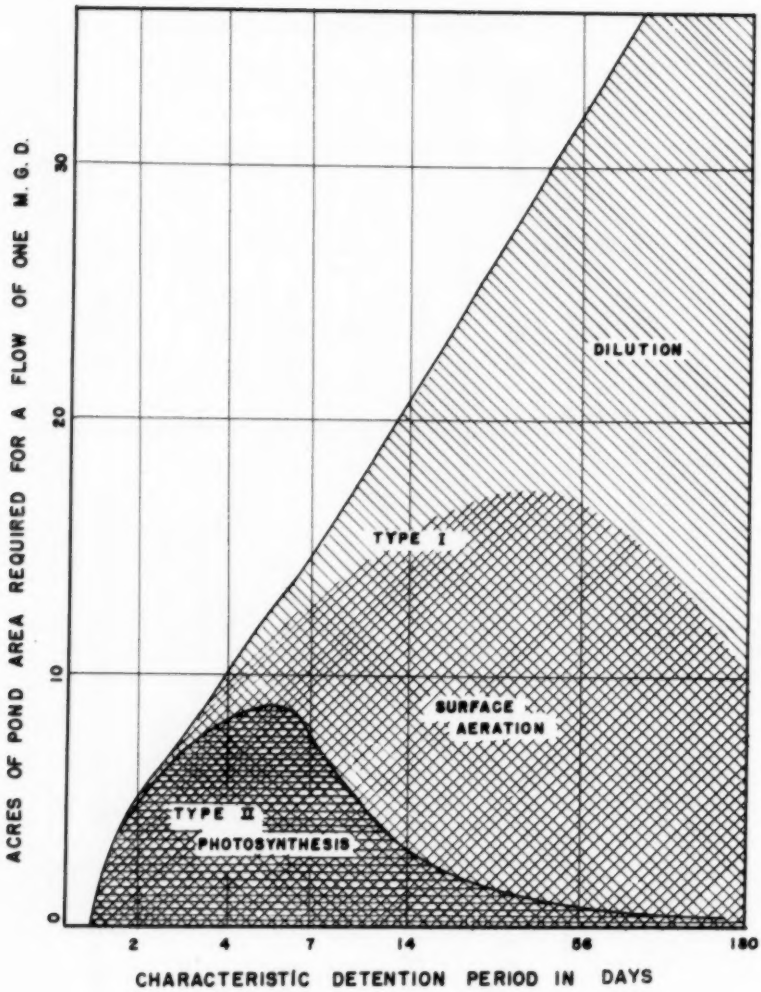


Fig. 1. General Types of Oxidation Ponds- Schematic Representation

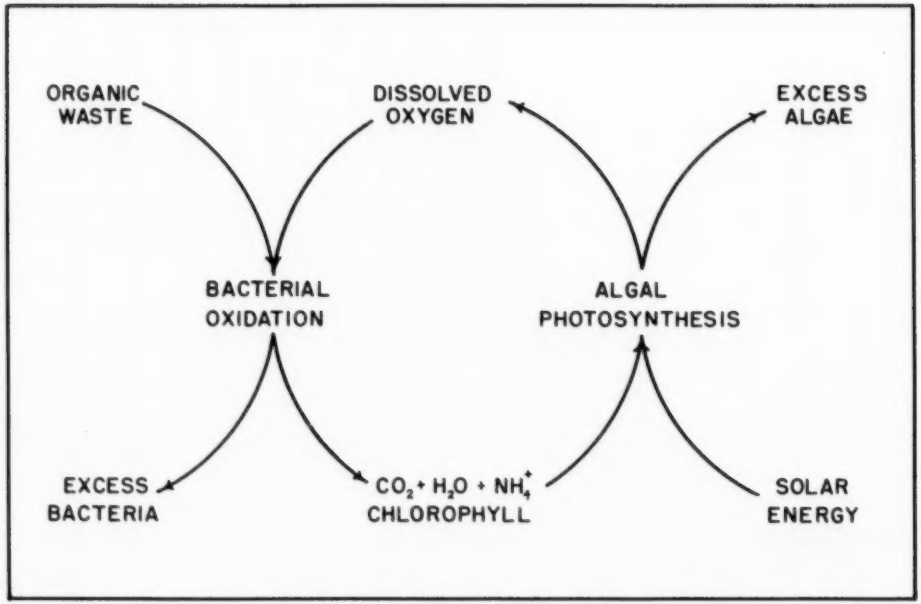


Fig. 2 The Cycle of Oxygen and Algal Production in Sewage Treatment by Photosynthesis

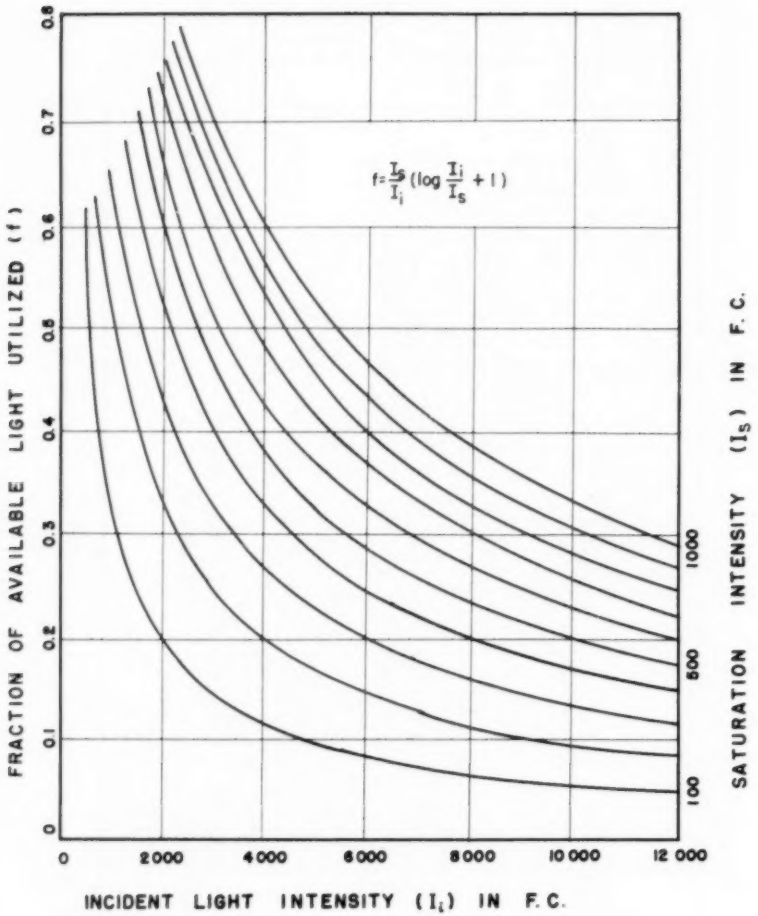
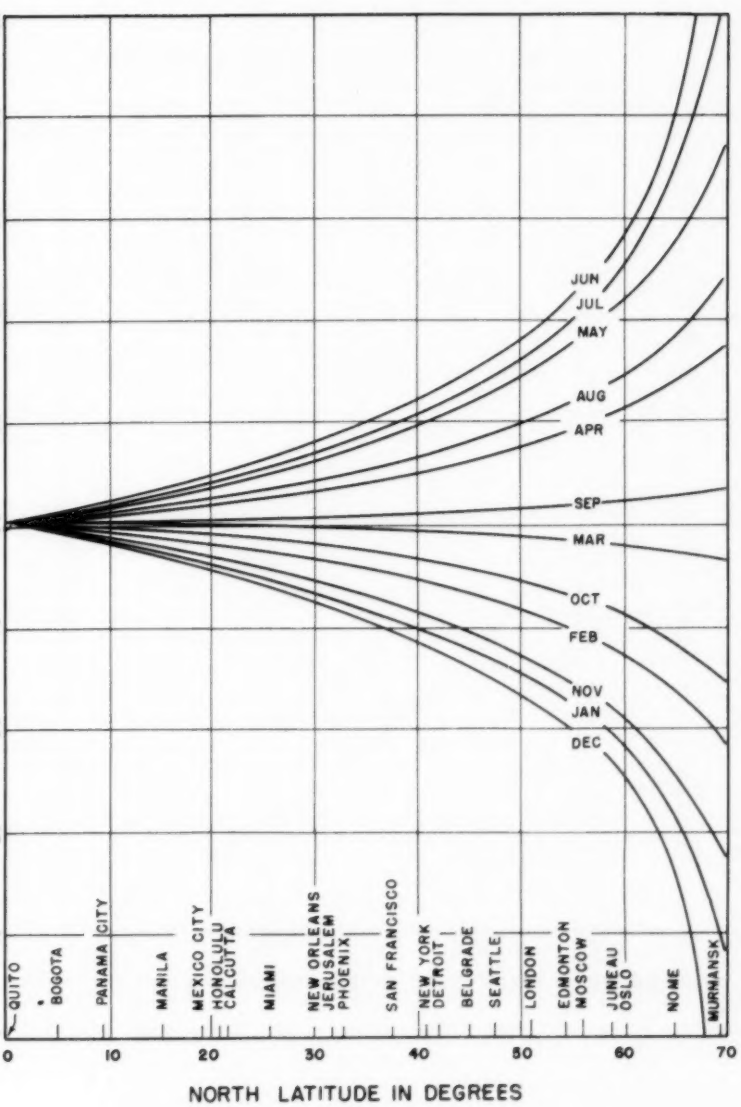


Figure 3. Influence of Saturation Intensity on Light Utilization by Algae


MEAN PERCENT OF TOTAL TIME SUN IS ABOVE THE HORIZON
NORTH LATITUDE IN DEGREES
0
10
20
30
40
50
60
70
80
90
100
JUN
JUL
MAY
AUG
APR
SEP
MAR
OCT
FEB
NOV
JAN
DEC
QUITO
BOGOTA
PANAMA CITY
MANILA
MEXICO CITY
HONOLULU
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MIAMI
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Fig. 4

92-989

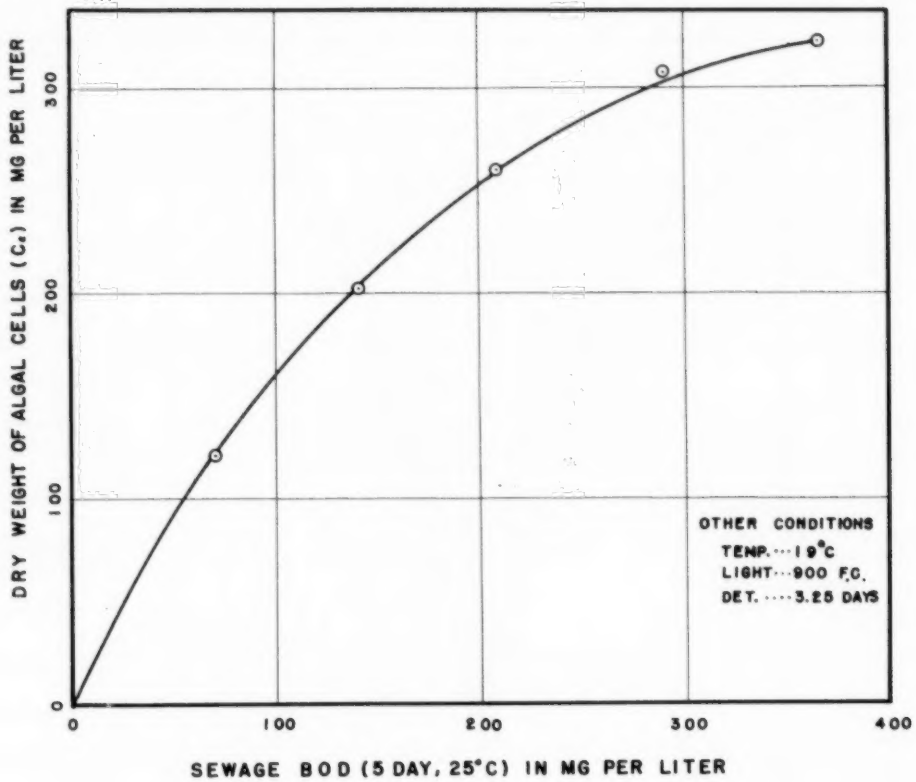

Figure 5. Effect of BOD on the Concentration of Algal Cells in Continuous Cultures

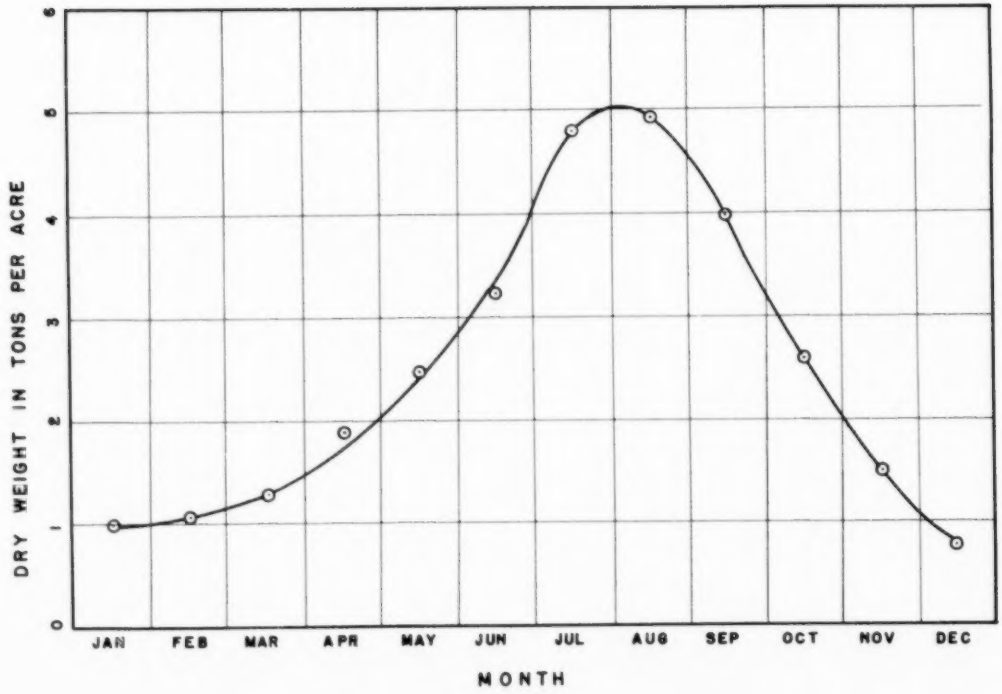

Figure 6. Estimated Monthly Yields of Algae from Domestic Sewage at Richmond, California

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

VOLUME 80 (1954)

MAY: 435(SM), 436(CP)[c], 437(HY)[c], 438(HY), 439(HY), 440(ST), 441(ST), 442(SA), 443(SA).

JUNE: 444(SM)[e], 445(SM)[e], 446(ST)[e], 447(ST)[e], 448(ST)[e], 449(ST)[e], 450(ST)[e], 451(ST)[e], 452(SA)[e], 453(SA)[e], 454(SA)[e], 455(SA)[e], 456(SM)[e].

JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

VOLUME 81 (1955)

JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

c. Discussion of several papers, grouped by Divisions.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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